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LETTERS

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Twist-controlled resonant tunnelling in graphene/boron nitride/graphene heterostructures

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2014

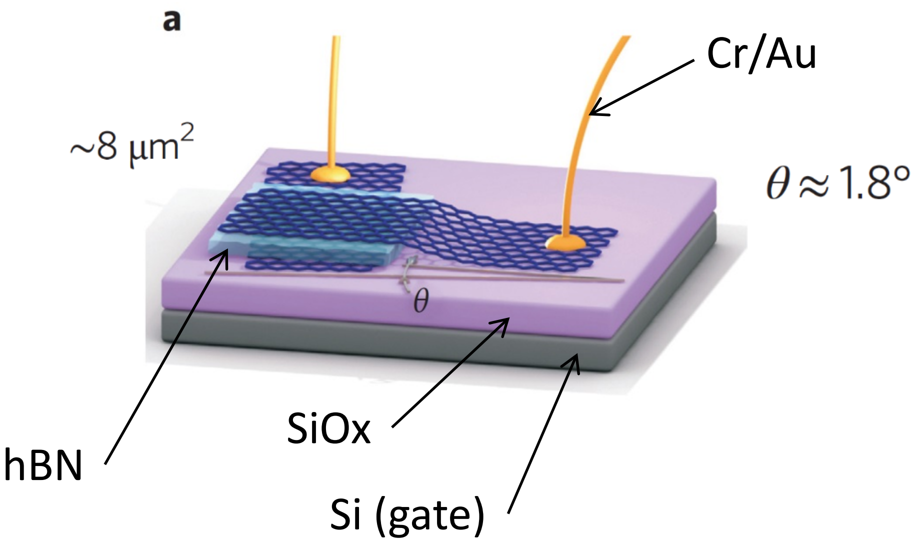
Taras Patlatiuk

23.11.2018

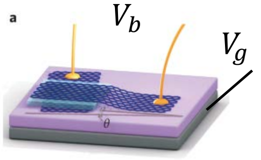
Motivation

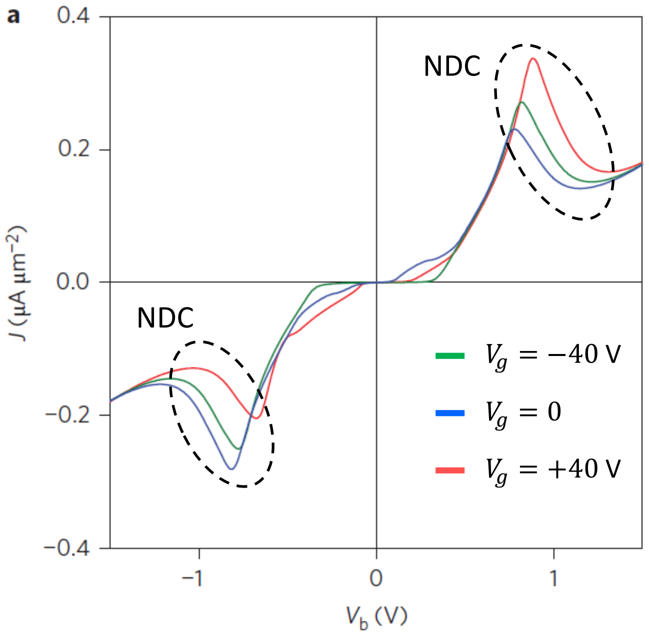
- Graphene-based high-frequency electronics
- Tunneling with conservation of energy and momentum
- Negative differential conductance (NDC)

Device

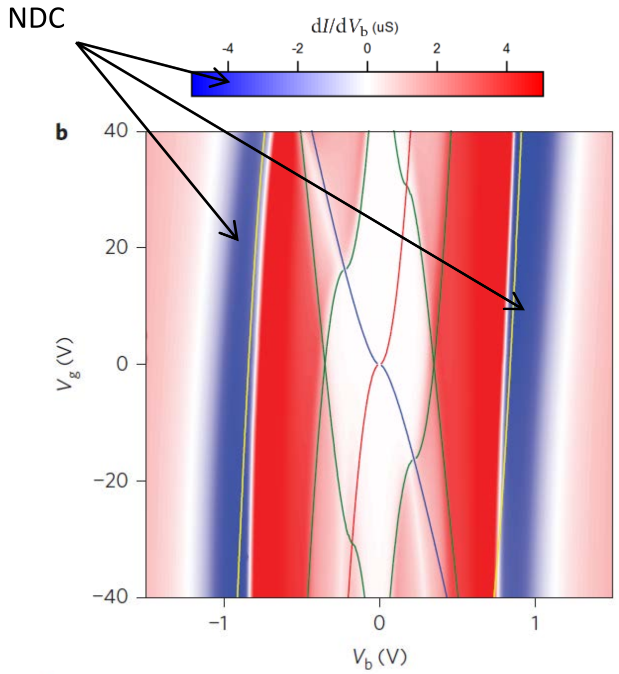


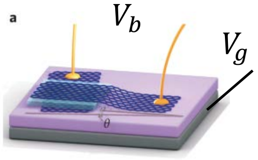
hBN thickness 1.4 nm (four layers)

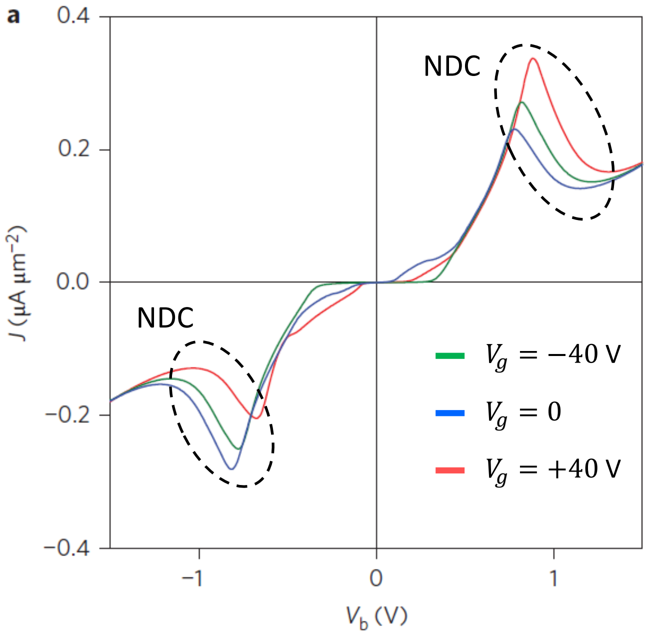




Differential conductance

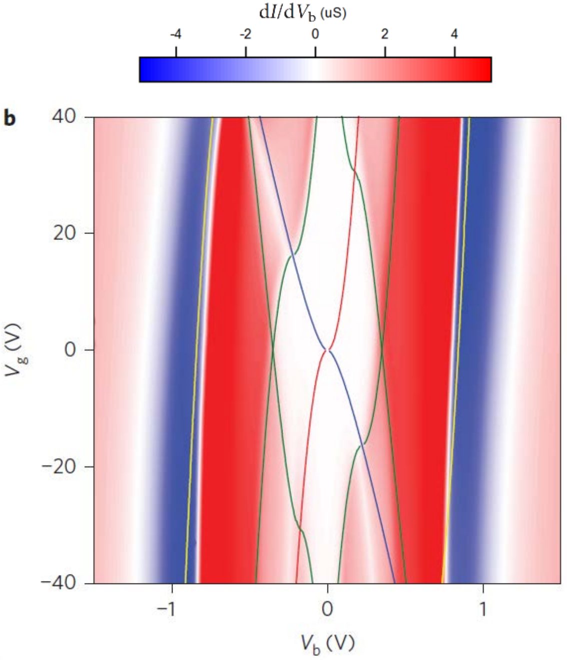




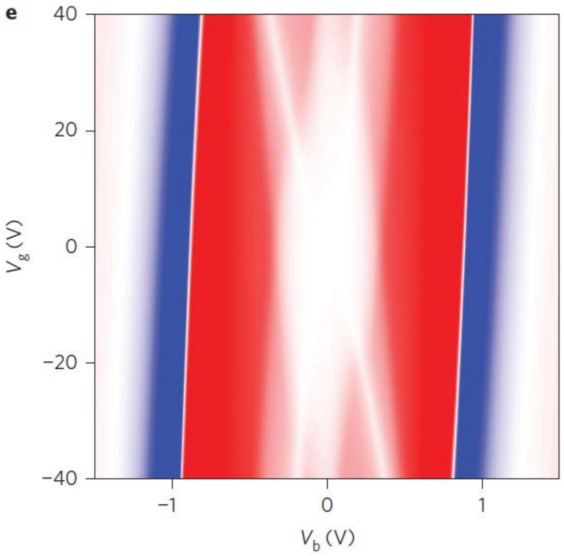


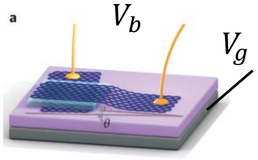
Differential conductance

Experiment

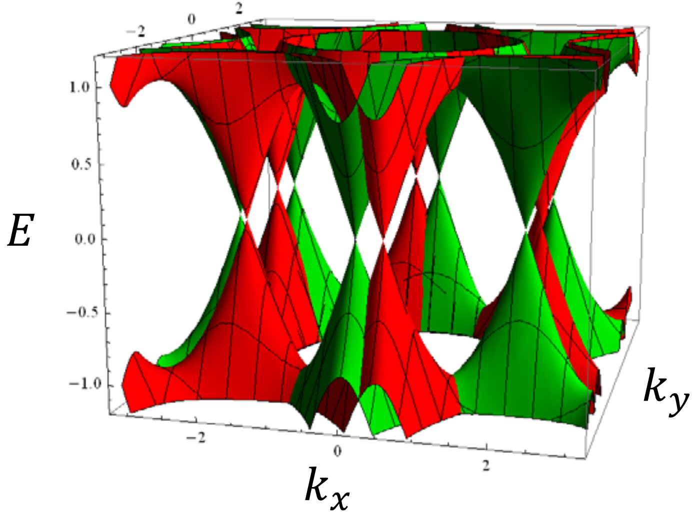


Simulations



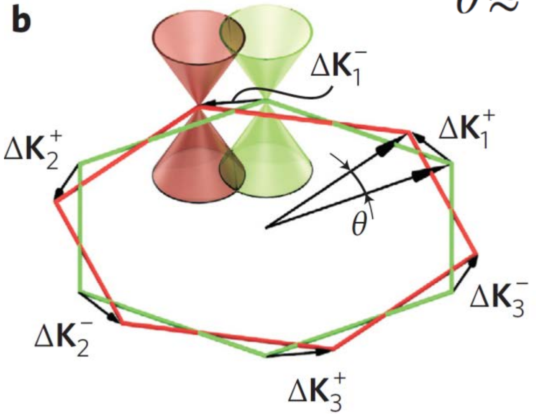


Band structure

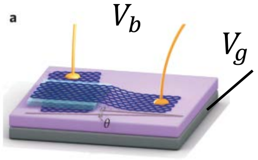


$\theta = \pi/20$

$\theta \approx 1.8°$

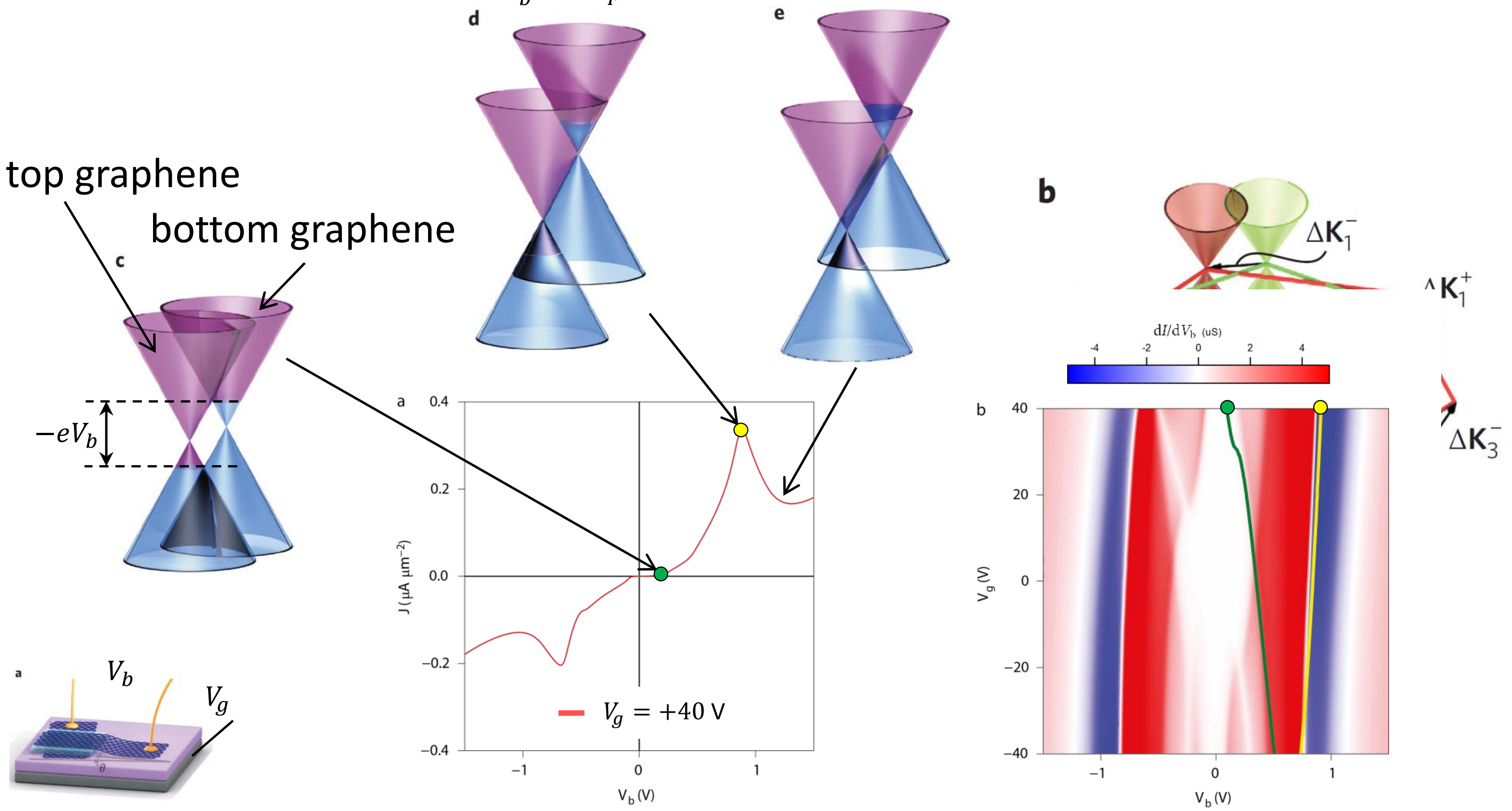


$$\Delta \mathbf{K}_i^{\pm} = \mathbf{l}_z \times \theta \mathbf{K}_i^{\pm}$$

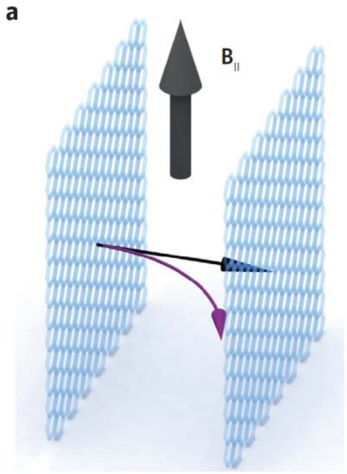


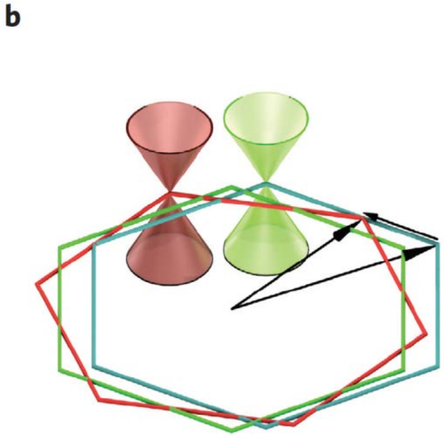
Model

$$-eV_b = \hbar v_F \Delta K$$

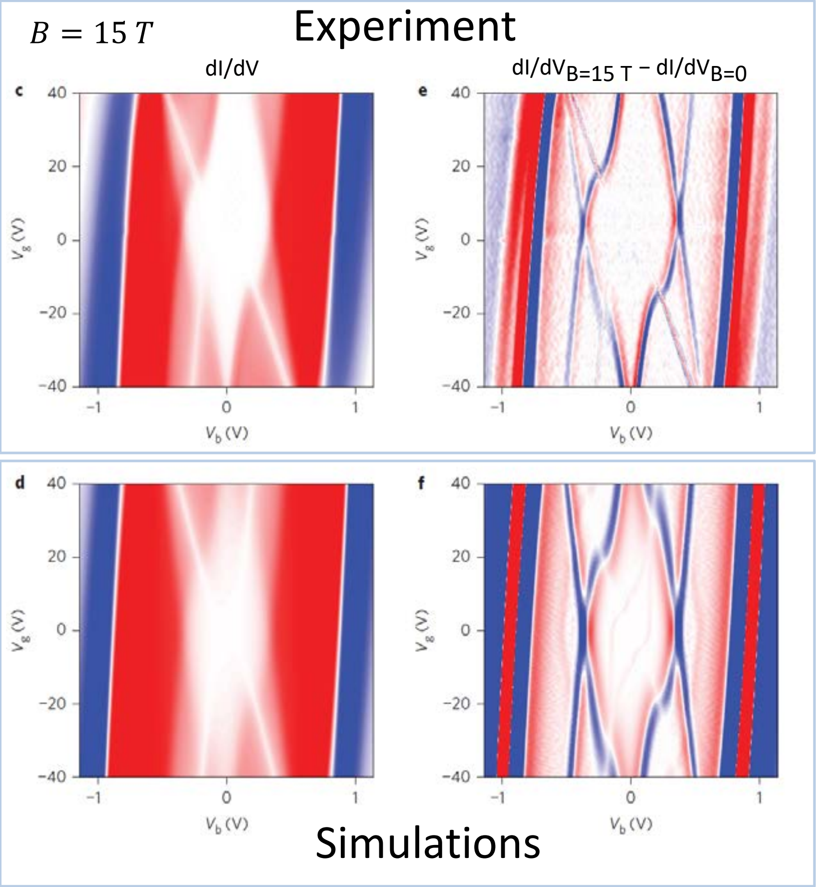


Magnetic field

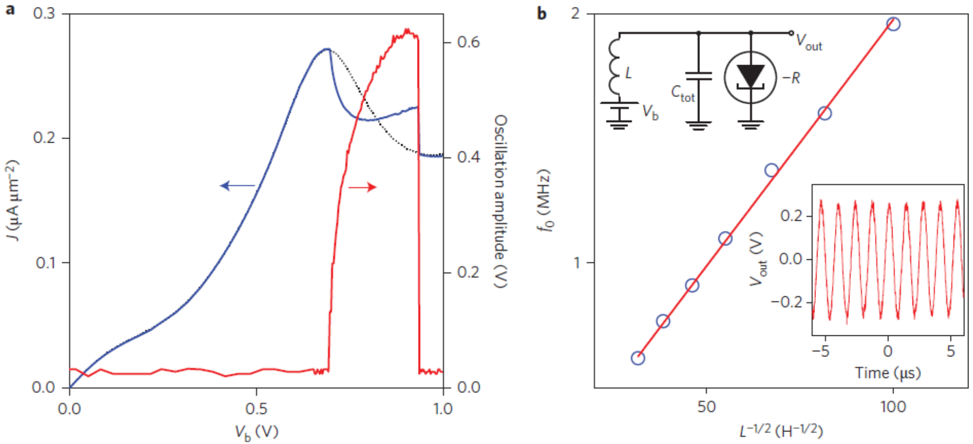




$$\hbar \Delta \mathbf{K}_i^{\pm} = \mathbf{l}_z \times \left[\theta \hbar \mathbf{K}_i^{\pm} + ed\mathbf{B}_{\parallel} \right]$$



NDC oscillator



$$f_0 = \frac{1}{2\pi\sqrt{L\, C_{tot}}}$$

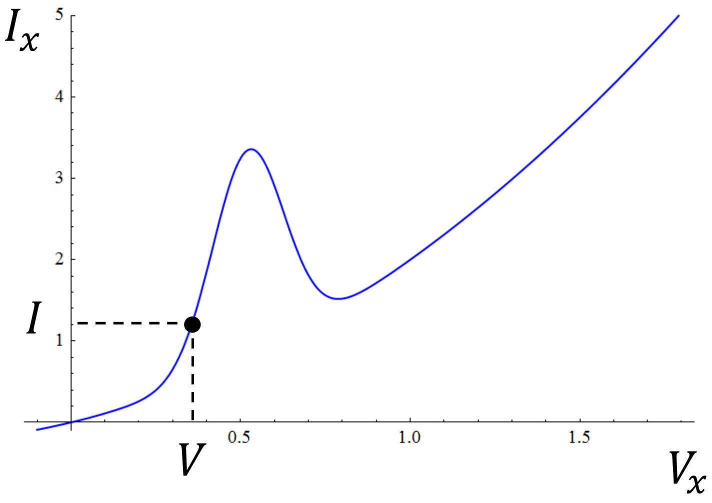
$$C_{tot} = 65\, pF$$

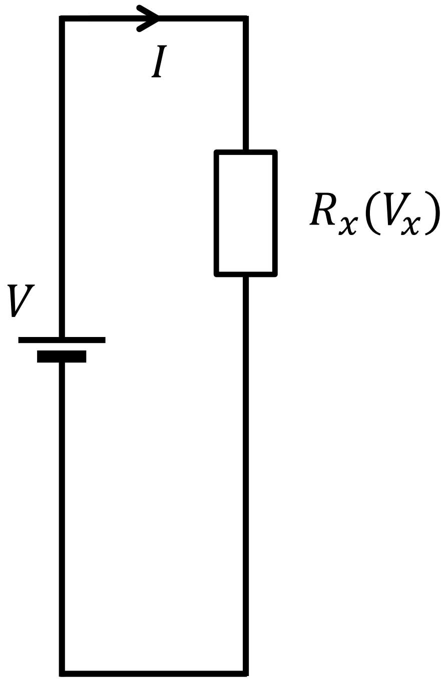
- $f_0 \sim MHz$
- parasitic capacitance limits f_0 (contact pads to Si gate)
- no carrier dwell time limitation
- potentially can operate in THz range

V_{amp}= 0.5 V

I-V characteristic

I-V characteristic of the element Rx

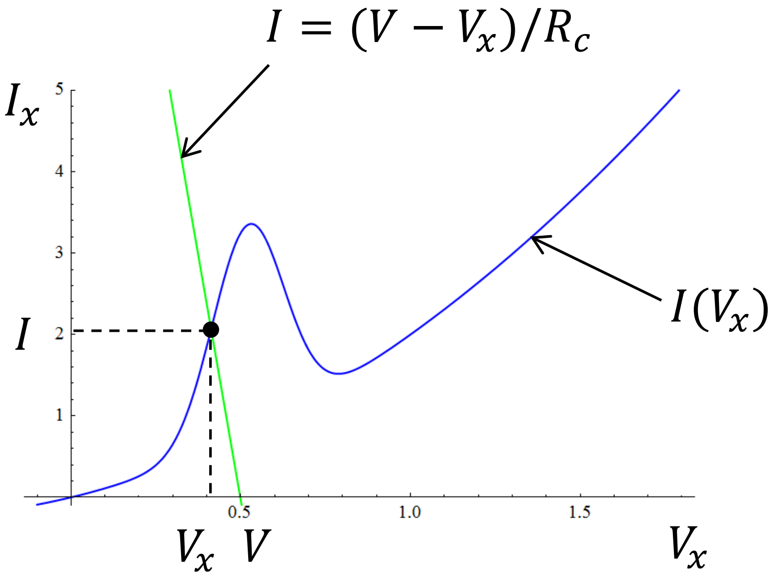


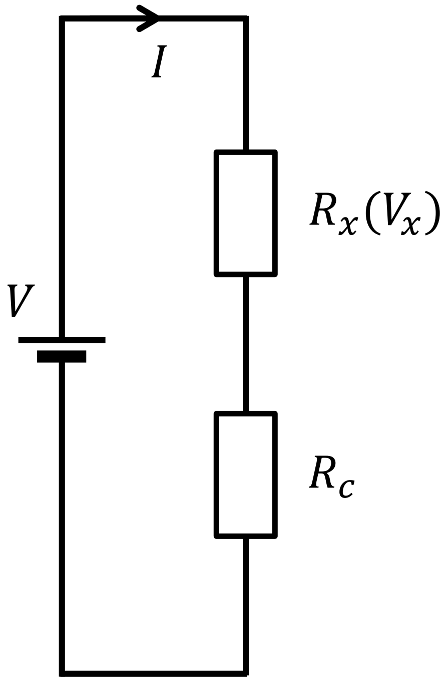


$$I = I_x$$

$$V = V_x$$

Load line





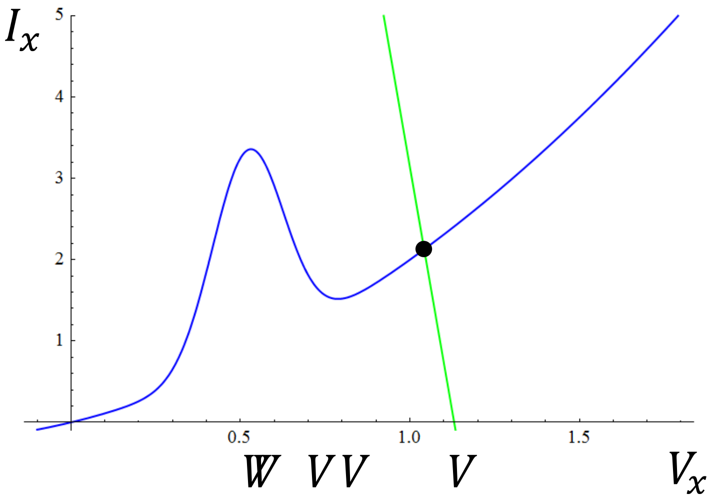
$$I = I_x$$

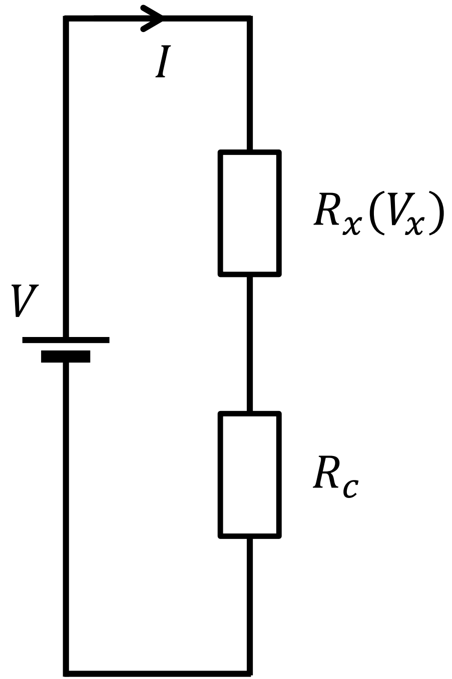
$$\cancel{V = V_x}$$

$$V = V_x + I\,R_c$$

$$I = (V - V_x)/R_c$$

Load line





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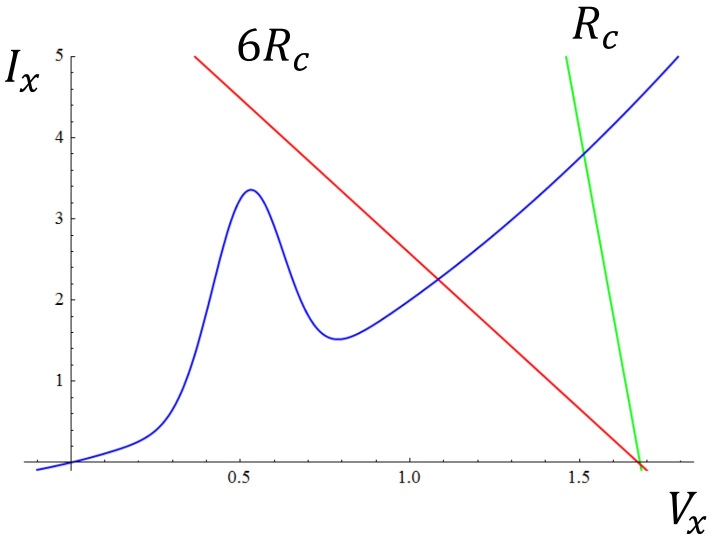

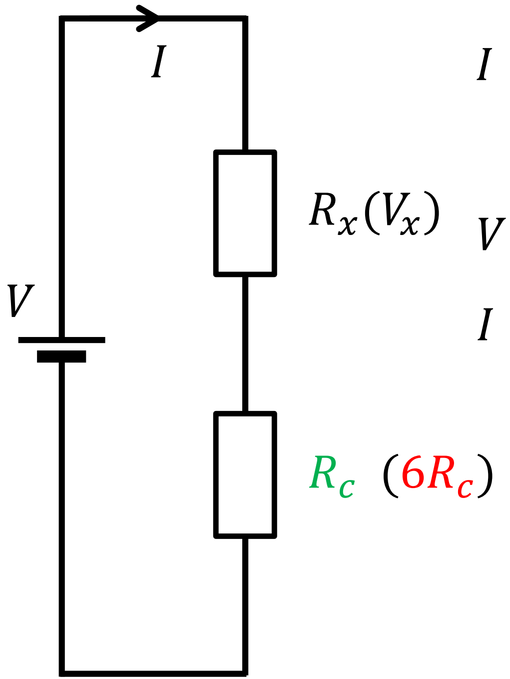

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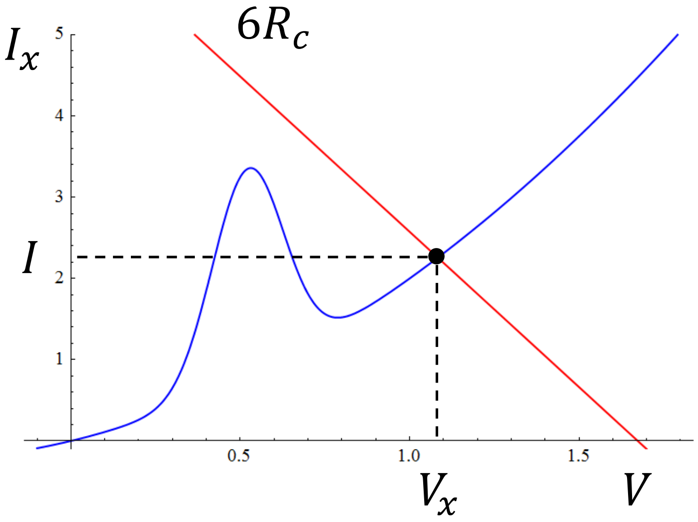

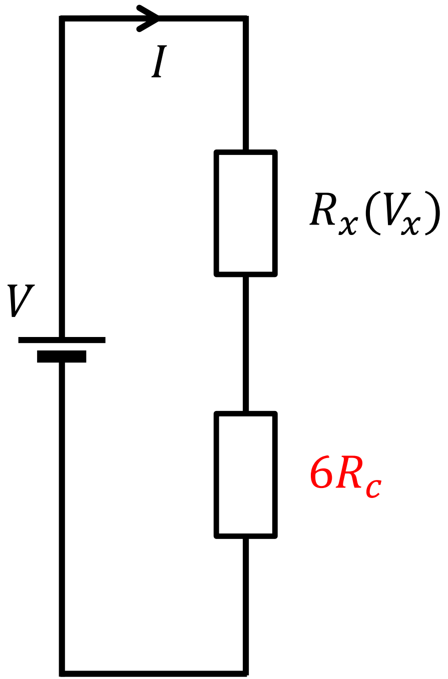

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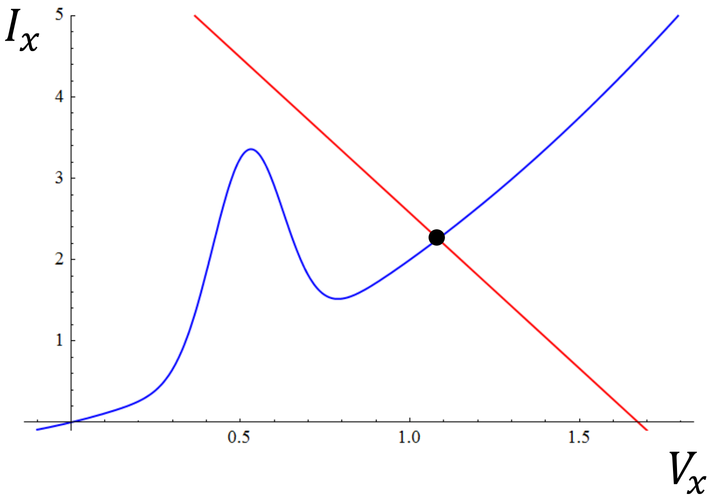

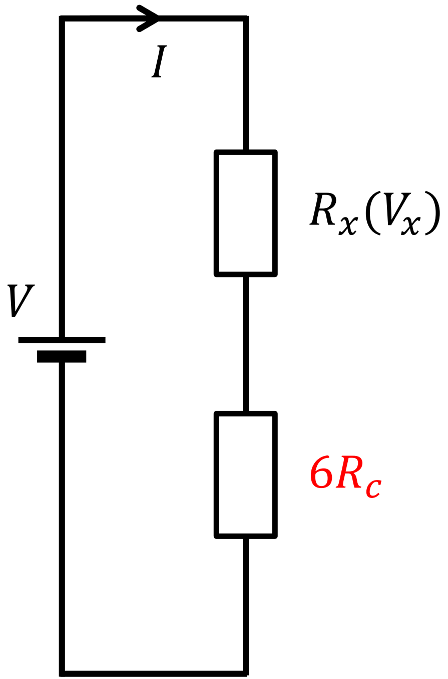

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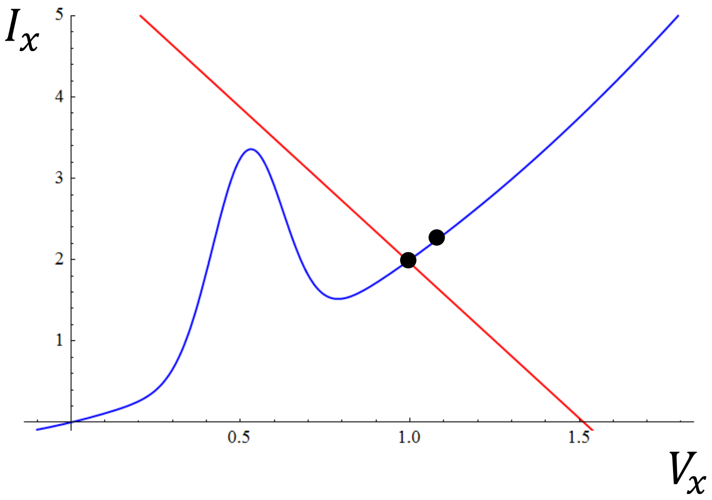

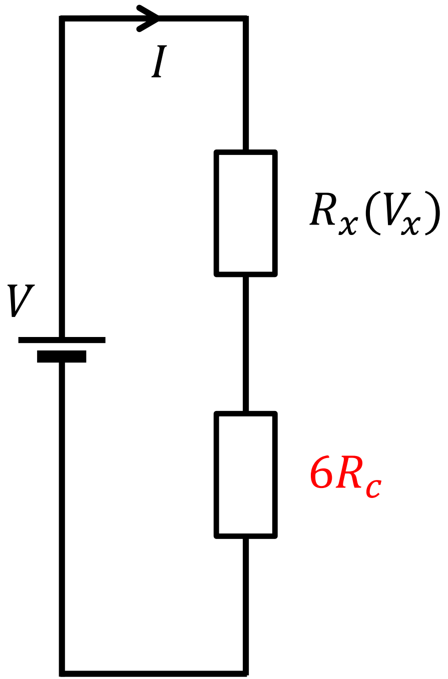

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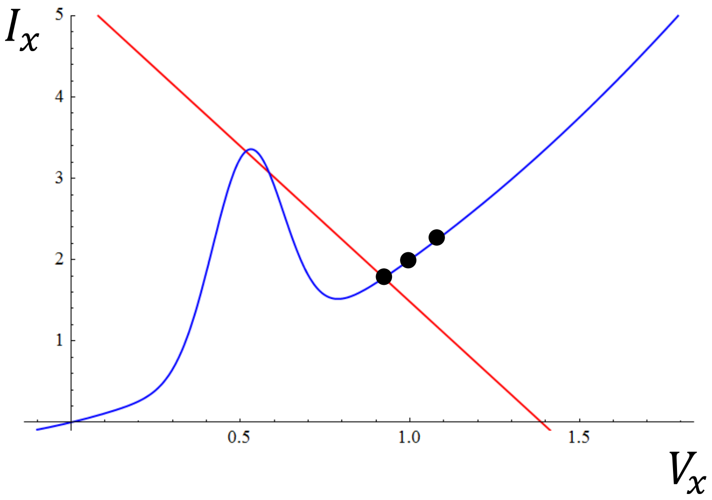

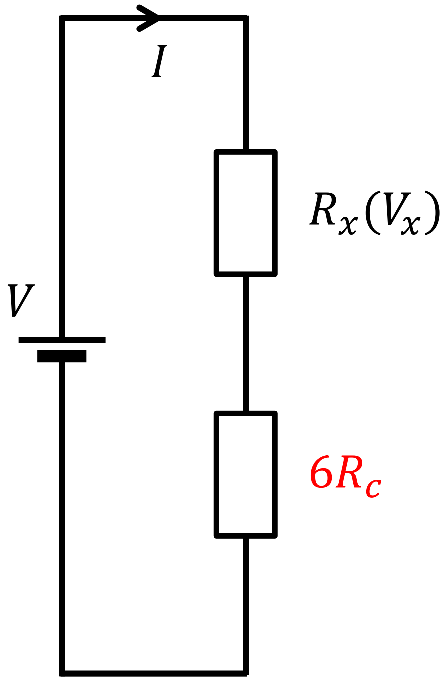

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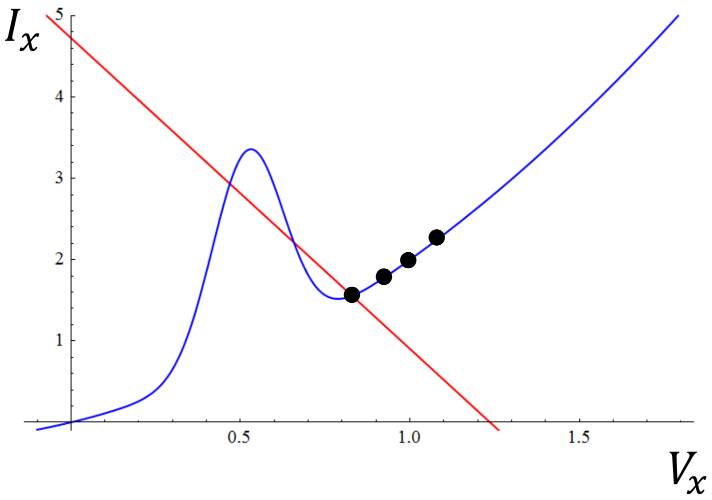

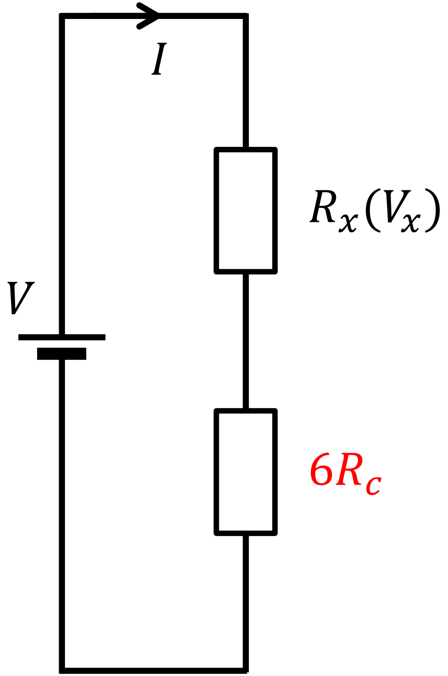

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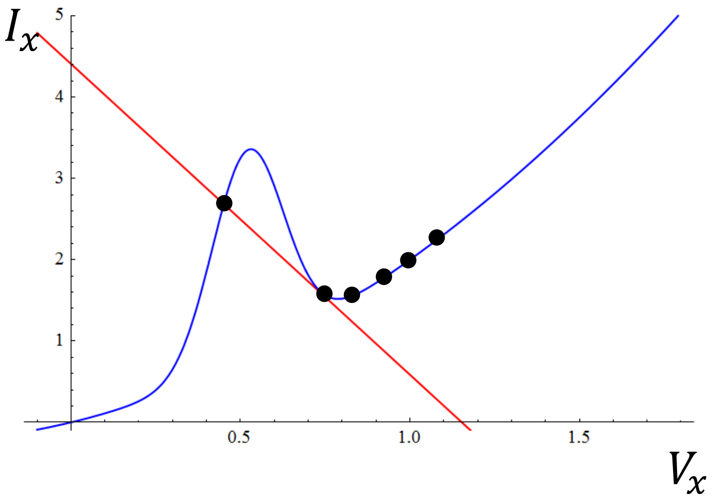

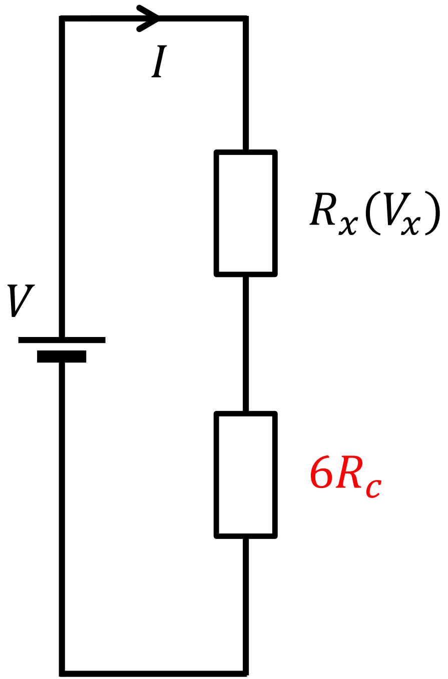

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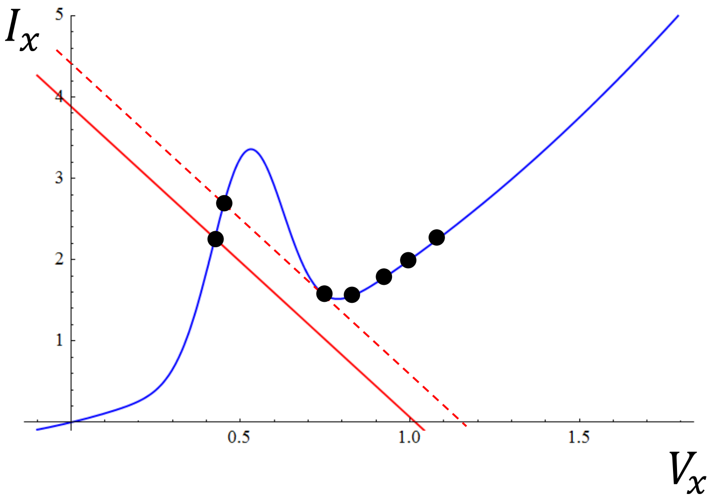

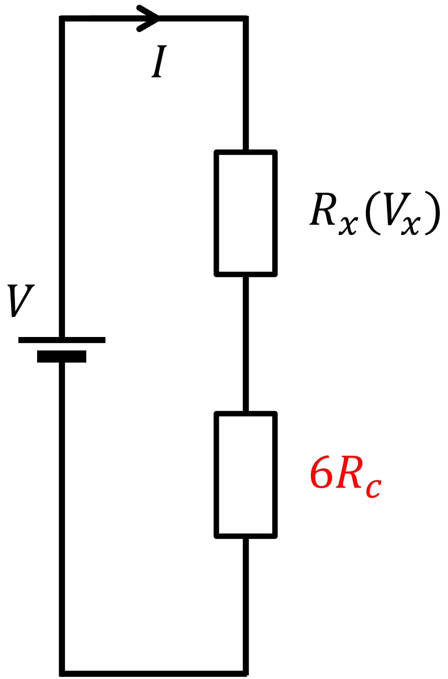

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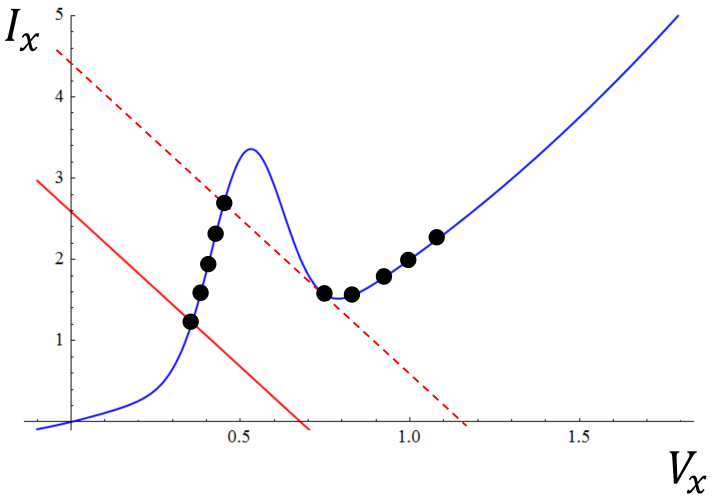

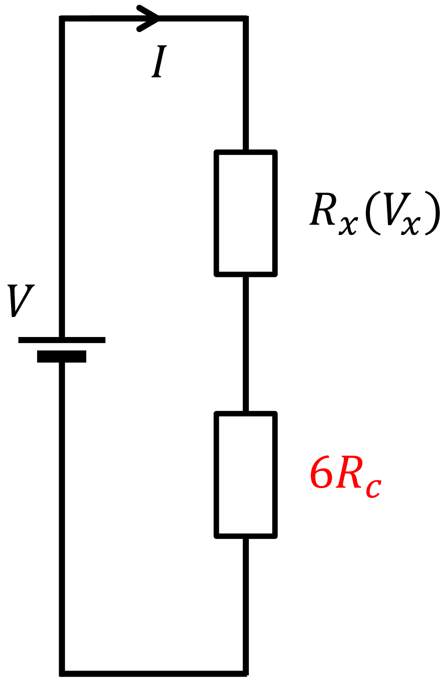

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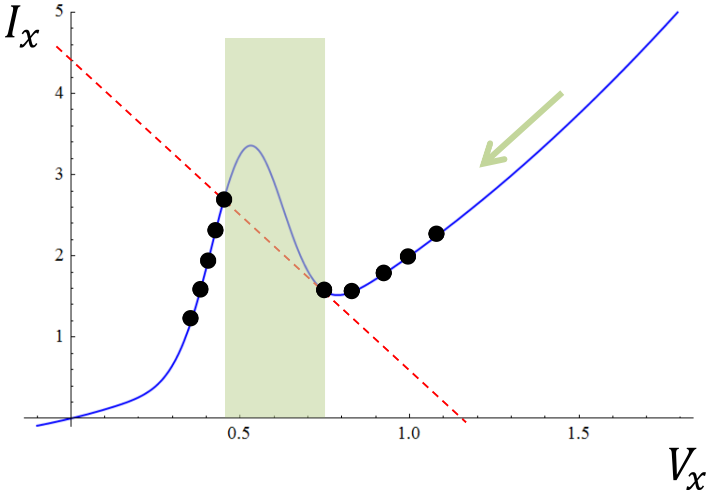

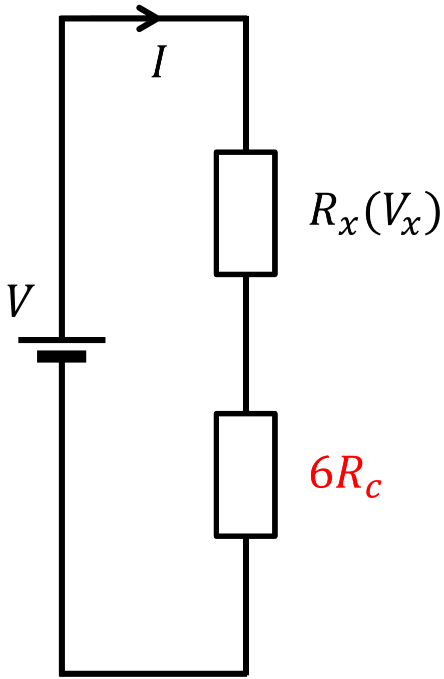

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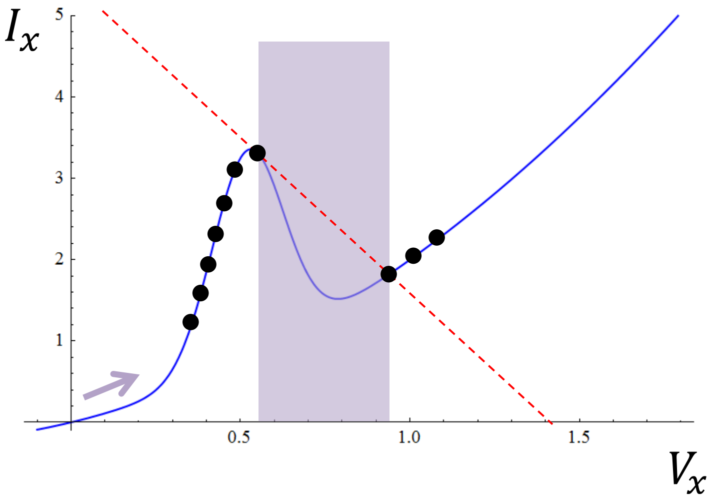

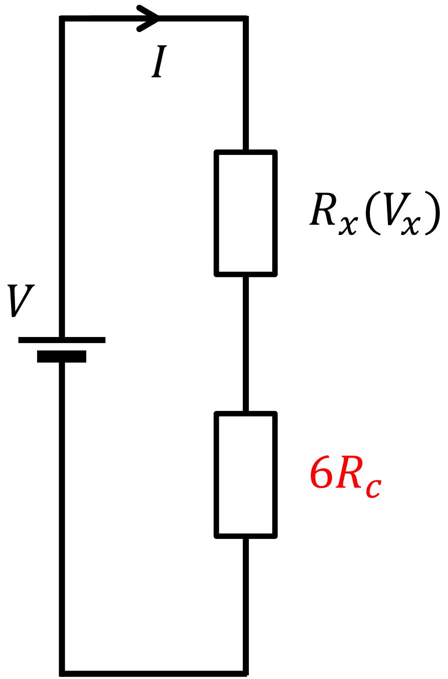

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$$V = V_x + I\ R_c$$

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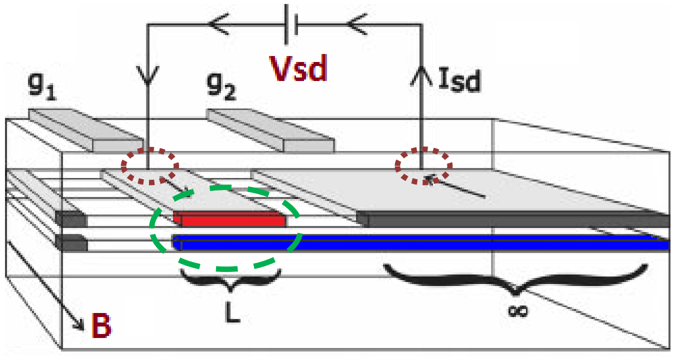
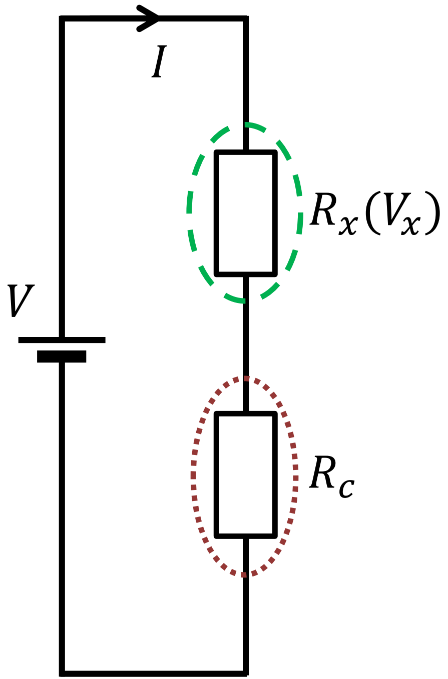
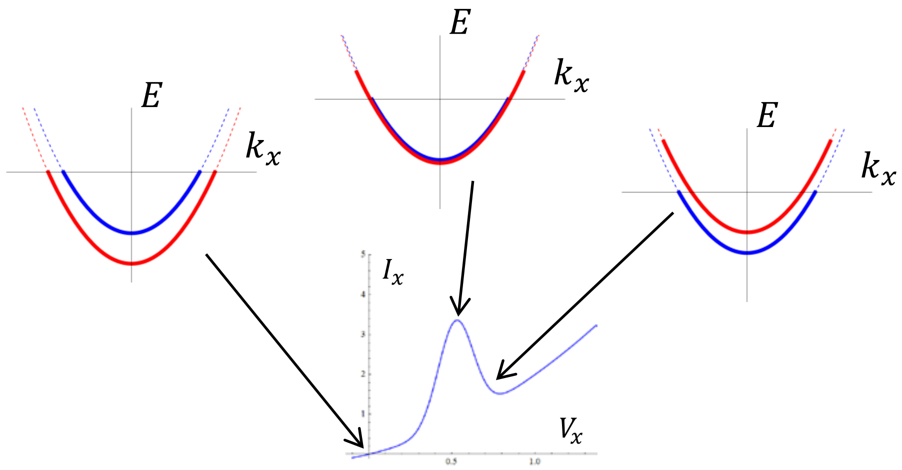
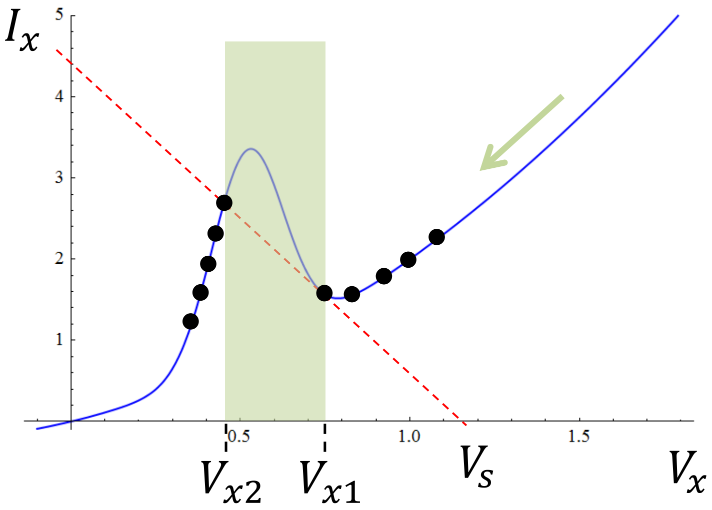
CEO wires



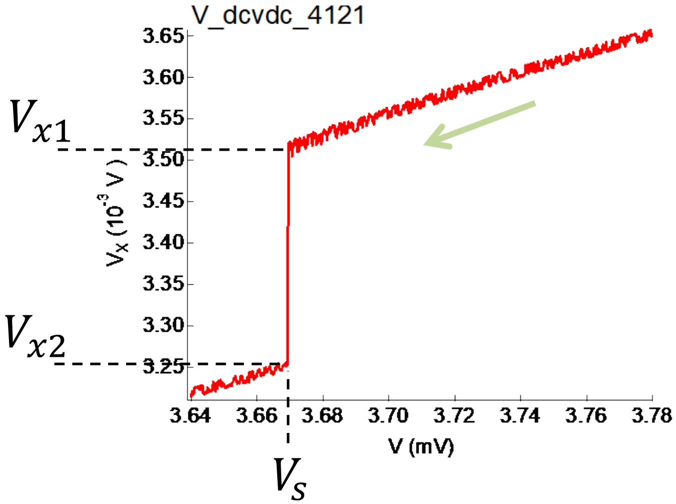




Switching

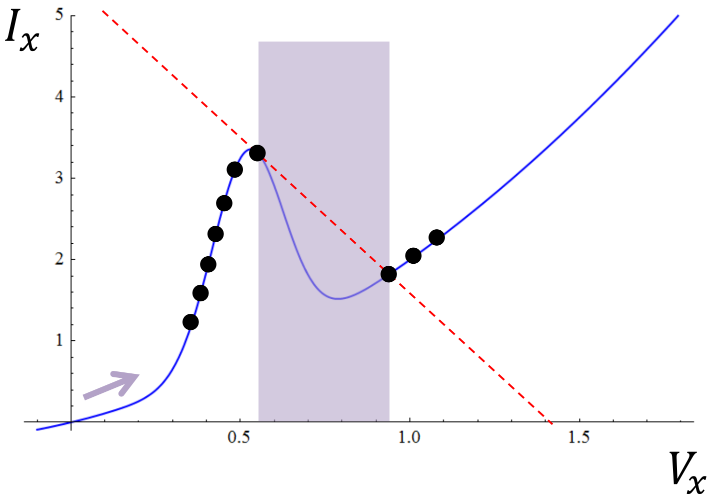


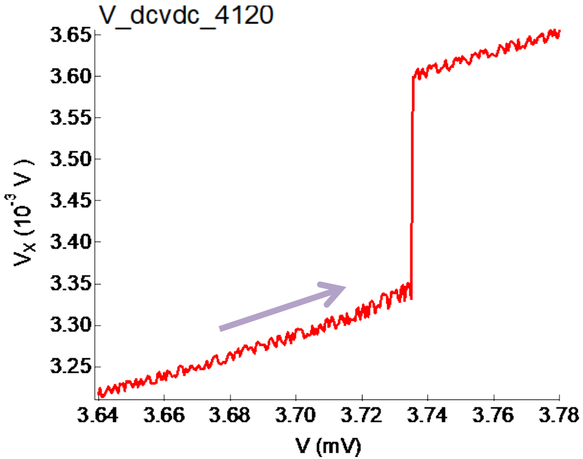
I_x
5
4
3
2
1
0.5
1.0
1.5
V_{x2}
V_{x1}
V_s
V_x



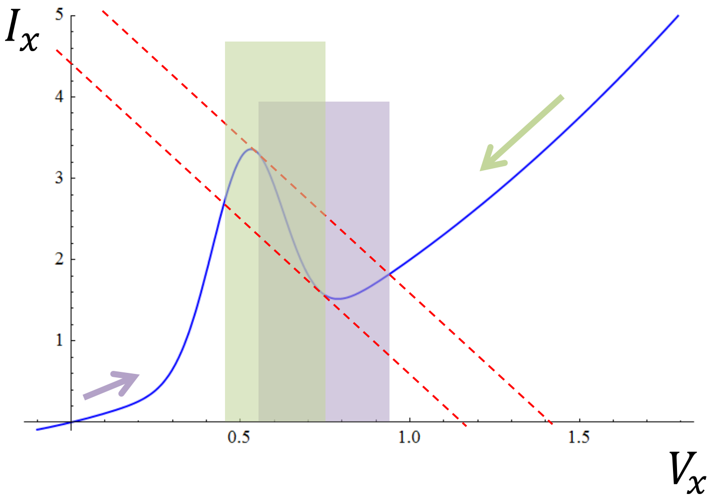
V_dcvdc_4121
3.65
3.60
3.55
3.50
3.45
3.40
3.35
3.30
3.25
V_X (10^{-3} V)
3.64
3.66
3.68
3.70
3.72
3.74
3.76
3.78
V (mV)
V_{x1}
V_{x2}
V_s

Switching

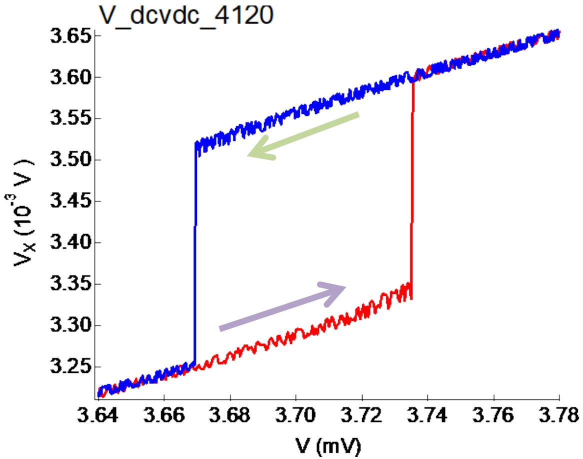

I_x
5
4
3
2
1
0.5
1.0
1.5
V_x


V_dcvdc_4120
3.65
3.60
3.55
3.50
3.45
3.40
3.35
3.30
3.25
V_X (10^{-3} V)
3.64
3.66
3.68
3.70
3.72
3.74
3.76
3.78
V (mV)

Hysteresis



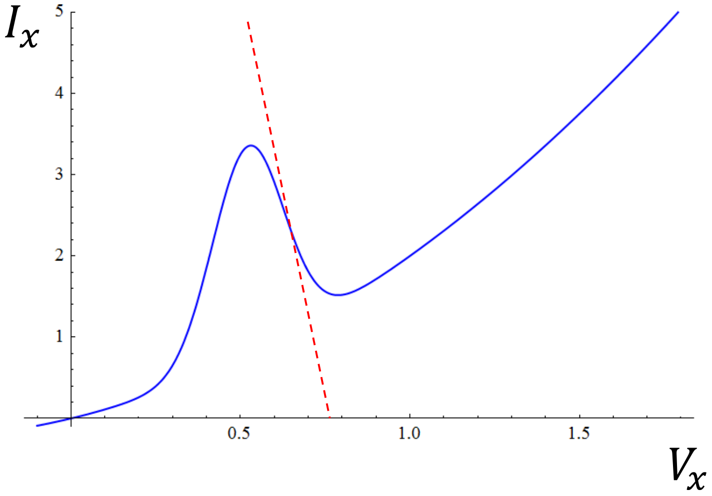
I_x
5
4
3
2
1
0.5
1.0
1.5
V_x

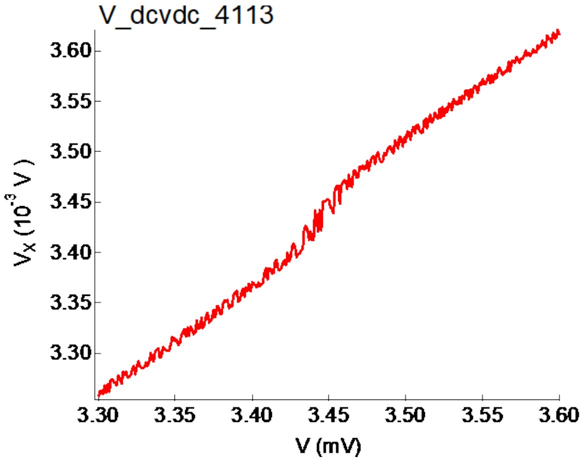


V_dcvdc_4120
3.65
3.60
3.55
3.50
3.45
3.40
3.35
3.30
3.25
V_X (10^{-3} V)
3.64
3.66
3.68
3.70
3.72
3.74
3.76
3.78
V (mV)

Good contacts

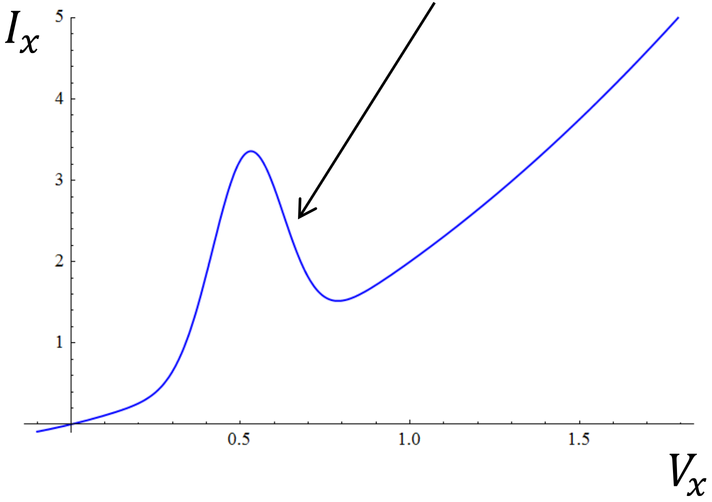
$$R_{c2} < R_{c1}$$

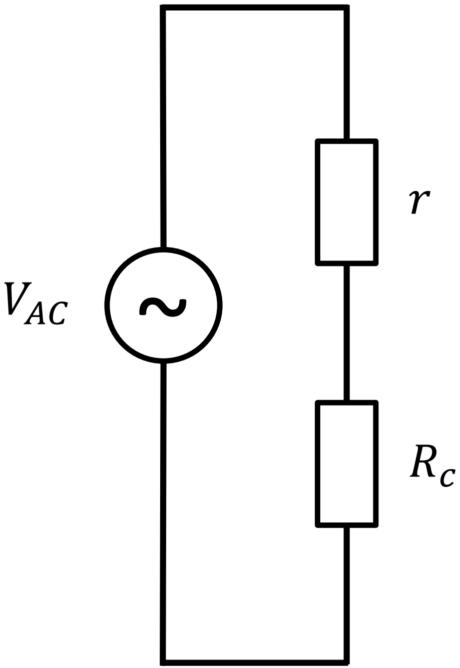




NDC amplifier

$$r = \frac{dI_x}{dV_x} < 0$$





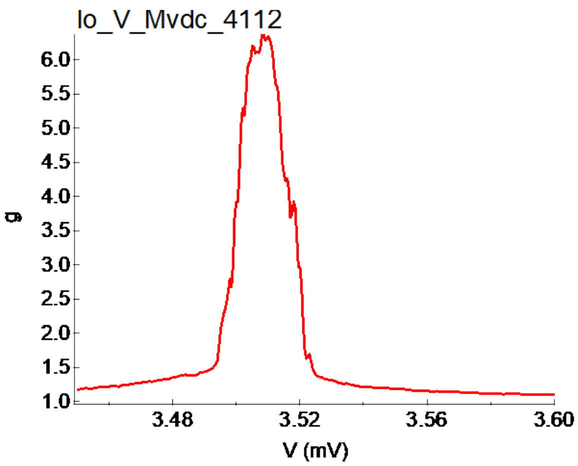
$$V_{x\,AC} = V_{AC}\,\frac{r}{R_c + r}$$

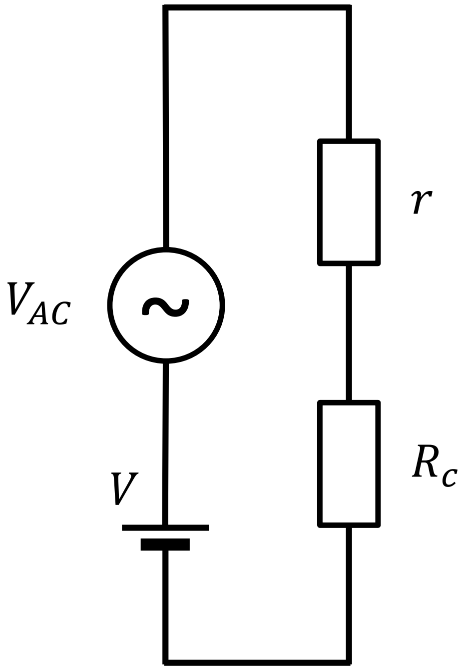
$$V_{x\,AC} = V_{AC}\,\frac{|r|}{R_c - |r|}$$

$$V_{x\,AC} = g\,V_{AC}$$

$$g = \frac{V_{x\,AC}}{V_{AC}}$$

NDC amplifier





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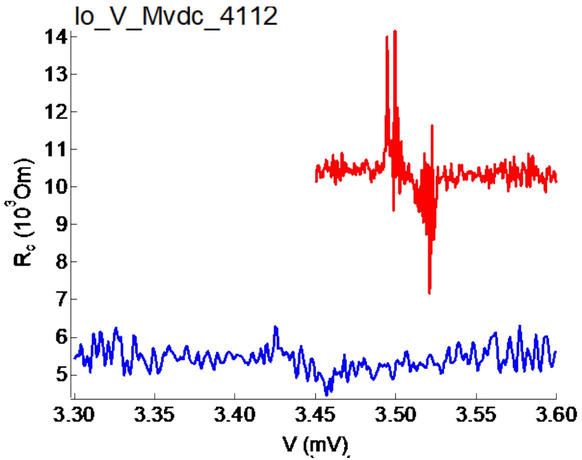
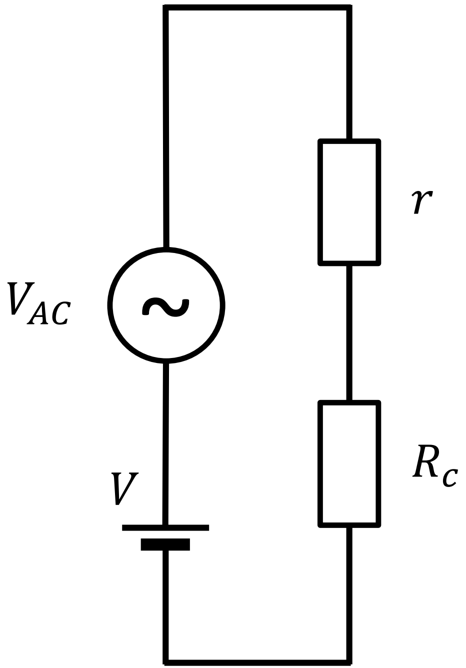
$$g = \frac{V_{x\,AC}}{V_{AC}}$$

NDC amplifier





$$V_{x\ AC} = V_{AC}\frac{r}{R_c + r}$$

$$V_{x\ AC} = V_{AC}\frac{-|r|}{R_c - |r|}$$

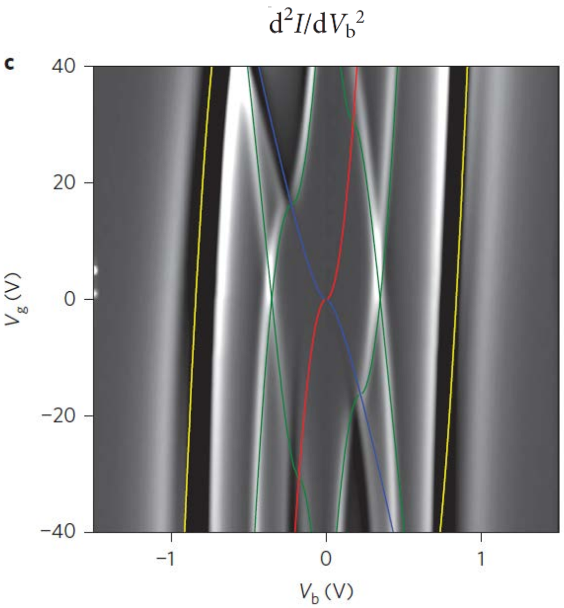
$$V_{x\ AC} = g\ V_{AC}$$

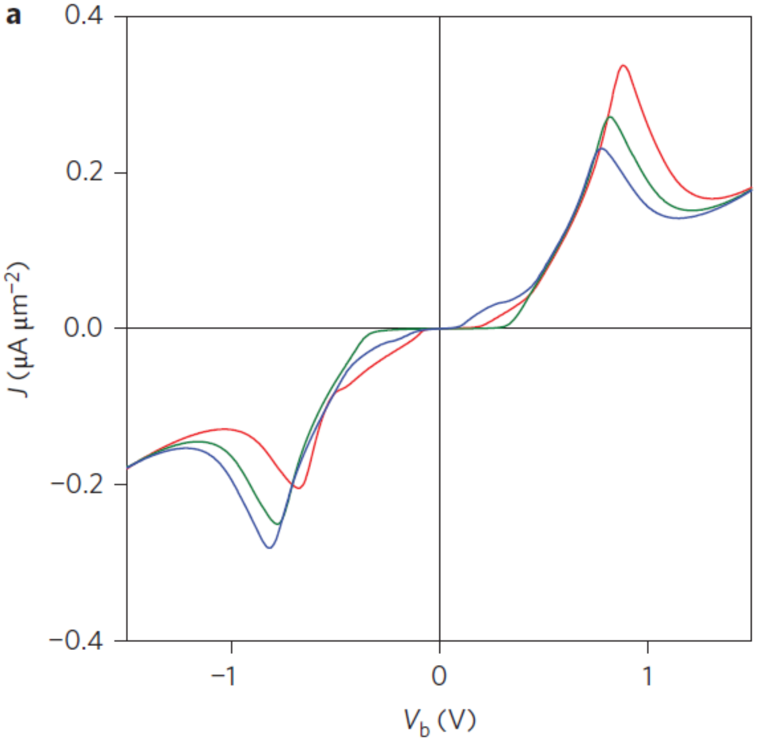
$$g = \frac{V_{x\ AC}}{V_{AC}} = \frac{-|r|}{R_c - |r|}$$

Conclusion

- Resonant tunneling in graphene
- Hysteresis, amplifications and oscillations based on NDC

Experiment


d²I/dV_b²
c
40
20
0
−20
−40
V_g (V)
−1
0
1
V_b (V)


a
0.4
0.2
0.0
−0.2
−0.4
J (μA μm⁻²)
−1
0
1
V_b (V)